

Measurement of Transverse Single-Spin Asymmetries for J/ψ Production in Polarized $p + p$ Collisions at $\sqrt{s} = 200$ GeV

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Abstract.

Transverse single spin asymmetries (SSAs) quantify the asymmetry of particle production relative to the transverse spin axis of a polarized hadron. SSAs have come to be recognized as a means of accessing QCD dynamics, both within initial-state hadrons and in the process of hadronization from partons. At $\sqrt{s} = 200$ GeV, heavy flavor single-spin asymmetries in proton-proton collisions provide access to gluon dynamics within the nucleon. Any large transverse single spin asymmetry observed in heavy flavor production can not originate from Collins effect because the gluon's transversity is zero. Therefore, the production of heavy flavor particles in the transversely polarized pp collisions at PHENIX experiment offers a good opportunity to gain information on the Sivers effect. Transverse single-spin asymmetries of J/ψ production may shed light on the long-standing question in QCD of the J/ψ production mechanism.

In this paper the first measurement of transverse SSAs in J/ψ production is presented. The data were taken by the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) during the 2006 and 2008 polarized proton run at $\sqrt{s} = 200$ GeV. The p_T and x_F dependencies are studied, for rapidity regions of $-2.2 < y < -1.2$, $|y| < 0.35$, and $1.2 < y < 2.2$, and p_T up to 6 GeV/c. Results were obtained as a function of J/ψ transverse momentum and Feynman- x .

1. Introduction

Transverse single-spin asymmetries (SSAs) quantify the asymmetry of particle production relative to the plane defined by the transverse spin axis and the momentum direction of a polarized hadron. SSAs have come to be recognized as a means of accessing QCD dynamics, both within initial-state hadrons and in the process of hadronization from partons. Large azimuthal transverse single-spin asymmetries of up to $\sim 40\%$ were first observed at large Feynman- x ($x_F = 2p_L/\sqrt{s}$, where p_L is the momentum along the beam direction) in pion production from transversely polarized proton-proton collisions at $\sqrt{s} = 4.9$ GeV in 1976 [?], contrary to theoretical expectations at the time [?], and subsequently observed in hadronic collisions over a range of energies extending up to $\sqrt{s} = 200$ GeV [?, ?, ?, ?, ?, ?, ?]. In recent years numerous measurements of transverse SSAs have been performed in semi-inclusive deep-inelastic scattering (SIDIS) off a transversely polarized proton or deuteron target as well [?, ?, ?, ?, ?, ?]. In order to describe the large transverse SSAs observed, two approaches have been developed since the 1990s, after early pioneering work by Efremov and Teryaev [?, ?]. One approach requires higher-twist contributions in the collinear factorization scheme, i.e. the exchange of a gluon between

one of the partons taking part in the hard scattering and the color field of either an initial- or final-state hadron. This was first proposed by Qiu and Sterman for gluon exchange in the initial state [?] and by Kanazawa and Koike for exchange in the final state [?]. Gluon exchange in either the initial or final state leads to terms including multiparton correlation functions, which can generate a non-zero SSA. The other approach utilizes parton distribution functions and/or fragmentation functions that are unintegrated in the partonic transverse momentum, k_T ; these functions are generally known as transverse-momentum-dependent distributions (TMDs). These two approaches have different but overlapping kinematic regimes of applicability and have been shown to correspond exactly in their region of overlap [?].

While higher-twist parton-nucleon spin-momentum correlation functions and TMDs were born within the nucleon structure community, as understanding of them matures, their implications for other areas of QCD are starting to be realized. J/ψ production has been extensively studied over the last decades, but the details of the production mechanism remain an open question (see ref. [?] for a comprehensive review), and an additional complication is that approximately 30%–40% of the measured J/ψ mesons in hadronic collisions are produced indirectly from feed-down from ψ' and χ_c [?]. It was proposed in 2008 by Yuan [?] that within the framework of non-relativistic QCD (NRQCD) [?], the transverse SSA of J/ψ production can be sensitive to the J/ψ production mechanism, assuming a non-zero gluon Sivvers function [?], which is a TMD that describes the correlation between the transverse spin of the proton and the k_T of the partons within it. Specifically, Yuan predicts that a non-zero gluon Sivvers function will produce a finite transverse SSA for color-singlet J/ψ production [?] in $p + p$ collisions, but the asymmetry should vanish for color-octet production [?] in $p + p$ due to cancelation between initial- and final-state effects, while a non-zero asymmetry for J/ψ production in SIDIS is only expected within the color-octet model. It should be noted that the relationship between the transverse SSA and the production mechanism is not quite as simple in the collinear higher-twist approach, with partial but not full cancelation of terms [?] in the cases where the asymmetry uniformly vanishes in the TMD approach presented by Yuan. Another important point to note regarding the TMD as compared to the collinear, higher-twist approach is that very recent theoretical work [?] suggests that factorization of hard processes in perturbative QCD (pQCD) into transverse-momentum-dependent distribution and fragmentation functions convoluted with partonic hard-scattering cross sections is not valid for processes involving more than two hadrons. Thus, in the process $p + p \rightarrow J/\psi + X$ a gluon Sivvers function may not be well defined; however, the definition within a factorized pQCD framework of the corresponding trigluon correlation functions in the collinear, higher-twist approach is believed to be valid.

Measurements of heavy flavor transverse SSAs in proton-proton collisions are of interest because they serve to isolate gluon dynamics within the nucleon, with heavy quarks being dominantly produced via gluon-gluon interactions. Very little is presently known about trigluon correlation functions or gluon TMDs. Measurements of the transverse momentum (p_T) spectrum of bottomonium production have been used to extract the k_T -unintegrated distribution of gluons in an unpolarized proton [?]. Similarly, measurements of open heavy flavor transverse SSAs have been proposed as a means to isolate gluon TMDs and/or their corresponding twist-three gluon correlation functions in polarized protons [?, ?, ?]. A previous PHENIX measurement of the transverse SSA in neutral pion production at midrapidity [?] as well as measurements by the COMPASS collaboration of the SSA in semi-inclusive charged hadron production [?], both consistent with zero, have been used to provide initial constraints on the gluon Sivvers function and suggest that it is small [?, ?], but further data relevant to gluon TMDs are greatly needed.

1.1. Headers, footers and page numbers

1.2. `jpconf.cls` package options

The `jpconf.cls` class file has two options ‘a4paper’ and ‘letterpaper’:

```
\documentclass[a4paper]{jpconf}

or

\documentclass[letterpaper]{jpconf}
```

Table 1. `jpconf.cls` class file options.

Option	Description
<code>a4paper</code>	Set the paper size and margins for A4 paper.
<code>letterpaper</code>	Set the paper size and margins for US letter paper.

The default paper size is A4 (i.e., the default option is `a4paper`) but this can be changed to Letter by using `\documentclass[letterpaper]{jpconf}`. It is essential that you do not put macros into the text which alter the page dimensions.

2. The title, authors, addresses and abstract

The code for setting the title page information is slightly different from the normal default in \LaTeX but please follow these instructions as carefully as possible so all articles within a conference have the same style to the title page. The title is set in bold unjustified type using the command `\title{#1}`, where `#1` is the title of the article. The first letter of the title should be capitalized with the rest in lower case. The next information required is the list of all authors' names followed by the affiliations. For the authors' names type `\author{#1}`, where `#1` is the list of all authors' names. The style for the names is initials then surname, with a comma after all but the last two names, which are separated by 'and'. Initials should *not* have full stops. First names may be used if desired. The command `\maketitle` is not required.

The addresses of the authors' affiliations follow the list of authors. Each address should be set by using `\address{#1}` with the address as the single parameter in braces. If there is more than one address then a superscripted number, followed by a space, should come at the start of each address. In this case each author should also have a superscripted number or numbers following their name to indicate which address is the appropriate one for them.

Please also provide e-mail addresses for any or all of the authors using an `\ead{#1}` command after the last address. `\ead{#1}` provides the text Email: so `#1` is just the e-mail address or a list of emails.

The abstract follows the addresses and should give readers concise information about the content of the article and should not normally exceed 200 words. **All articles must include an abstract.** To indicate the start of the abstract type `\begin{abstract}` followed by the text of the abstract. The abstract should normally be restricted to a single paragraph and is terminated by the command `\end{abstract}`

2.1. Sample coding for the start of an article

The code for the start of a title page of a typical paper might read:

```
\title{The anomalous magnetic moment of the
neutrino and its relation to the solar neutrino problem}
```

```
\author{P J Smith$^1$, T M Collins$^2$,
R J Jones$^{3,}$}\footnote[4]{Present address:
```

Department of Physics, University of Bristol, Tyndalls Park Road,
Bristol BS8 1TS, UK.} and Janet Williams\$^3\$}

\address{\$^1\$ Mathematics Faculty, Open University,
Milton Keynes MK7~6AA, UK}

\address{\$^2\$ Department of Mathematics,
Imperial College, Prince Consort Road, London SW7~2BZ, UK}

\address{\$^3\$ Department of Computer Science,
University College London, Gower Street, London WC1E~6BT, UK}

\ead{williams@ucl.ac.uk}

\begin{abstract}

The abstract appears here.

\end{abstract}

3. The text

The text of the article should be produced using standard L^AT_EX formatting. Articles may be divided into sections and subsections, but the length limit provided by the conference organizer should be adhered to.

3.1. Acknowledgments

Authors wishing to acknowledge assistance or encouragement from colleagues, special work by technical staff or financial support from organizations should do so in an unnumbered Acknowledgments section immediately following the last numbered section of the paper. The command \ack sets the acknowledgments heading as an unnumbered section.

3.2. Appendices

Technical detail that it is necessary to include, but that interrupts the flow of the article, may be consigned to an appendix. Any appendices should be included at the end of the main text of the paper, after the acknowledgments section (if any) but before the reference list. If there are two or more appendices they will be called Appendix A, Appendix B, etc. Numbered equations will be in the form (A.1), (A.2), etc, figures will appear as figure A1, figure B1, etc and tables as table A1, table B1, etc.

The command \appendix is used to signify the start of the appendixes. Thereafter \section, \subsection, etc, will give headings appropriate for an appendix. To obtain a simple heading of ‘Appendix’ use the code \section*{Appendix}. If it contains numbered equations, figures or tables the command \appendix should precede it and \setcounter{section}{1} must follow it.

4. References

In the online version of *Journal of Physics: Conference Series* references will be linked to their original source or to the article within a secondary service such as INSPEC or ChemPort wherever possible. To facilitate this linking extra care should be taken when preparing reference lists.

Two different styles of referencing are in common use: the Harvard alphabetical system and the Vancouver numerical system. For *Journal of Physics: Conference Series*, the Vancouver numerical system is preferred but authors should use the Harvard alphabetical system if they wish to do so. In the numerical system references are numbered sequentially throughout the text within square brackets, like this [2], and one number can be used to designate several references.

4.1. Using BibTeX

We highly recommend the `iopart-num` BibTeX package by Mark A Caprio [?], which is included with this documentation.

4.2. Reference lists

A complete reference should provide the reader with enough information to locate the article concerned, whether published in print or electronic form, and should, depending on the type of reference, consist of:

- name(s) and initials;
- date published;
- title of journal, book or other publication;
- titles of journal articles may also be included (optional);
- volume number;
- editors, if any;
- town of publication and publisher in parentheses for *books*;
- the page numbers.

Up to ten authors may be given in a particular reference; where there are more than ten only the first should be given followed by ‘*et al*’. If an author is unsure of a particular journal’s abbreviated title it is best to leave the title in full. The terms *loc. cit.* and *ibid.* should not be used. Unpublished conferences and reports should generally not be included in the reference list and articles in the course of publication should be entered only if the journal of publication is known. A thesis submitted for a higher degree may be included in the reference list if it has not been superseded by a published paper and is available through a library; sufficient information should be given for it to be traced readily.

4.3. Formatting reference lists

Numeric reference lists should contain the references within an unnumbered section (such as `\section*{References}`). The reference list itself is started by the code `\begin{thebibliography}{<num>}`, where `<num>` is the largest number in the reference list and is completed by `\end{thebibliography}`. Each reference starts with `\bibitem{<label>}`, where ‘label’ is the label used for cross-referencing. Each `\bibitem` should only contain a reference to a single article (or a single article and a preprint reference to the same article). When one number actually covers a group of two or more references to different articles, `\nonum` should replace `\bibitem{<label>}` at the start of each reference in the group after the first.

For an alphabetic reference list use `\begin{thereferences} ... \end{thereferences}` instead of the ‘thebibliography’ environment and each reference can be start with just `\item` instead of `\bibitem{label}` as cross referencing is less useful for alphabetic references.

4.4. References to printed journal articles

A normal reference to a journal article contains three changes of font (see table ??) and is constructed as follows:

-

A typical (numerical) reference list might begin

[1] Strite S and Morkoc H 1992 *J. Vac. Sci. Technol. B* **10** 1237

which would be obtained by typing

Table 2. Font styles for a reference to a journal article.

Element	Style
Authors	Roman type
Date	Roman type
Article title (optional)	Roman type
Journal title	Italic type
Volume number	Bold type
Page numbers	Roman type

4.5. References to *Journal of Physics: Conference Series* articles

Each conference proceeding published in *Journal of Physics: Conference Series* will be a separate volume; references should follow the style for conventional printed journals. For example:

[1] Douglas G 2004 *J. Phys.: Conf. Series* **1** 23–36

4.6. References to preprints

For preprints there are two distinct cases:

- (1) Where the article has been published in a journal and the preprint is supplementary reference information. In this case it should be presented as:

[1] Kunze K 2003 T-duality and Penrose limits of spatially homogeneous and inhomogeneous cosmologies *Phys. Rev. D* **68** 063517 (*Preprint* gr-qc/0303038)

- (2) Where the only reference available is the preprint. In this case it should be presented as

[1] Milson R, Coley A, Pravda V and Pravdova A 2004 Alignment and algebraically special tensors *Preprint* gr-qc/0401010

4.7. References to electronic-only journals

In general article numbers are given, and no page ranges, as most electronic-only journals start each article on page 1.

- For *New Journal of Physics* (article number may have from one to three digits)

[1] Fischer R 2004 Bayesian group analysis of plasma-enhanced chemical vapour deposition data *New. J. Phys.* **6** 25

- For SISSA journals the volume is divided into monthly issues and these form part of the article number

[1] Horowitz G T and Maldacena J 2004 The black hole final state *J. High Energy Phys.* JHEP02(2004)008

[2] Bentivegna E, Bonanno A and Reuter M 2004 Confronting the IR fixed point cosmology with high-redshift observations *J. Cosmol. Astropart. Phys.* JCAP01(2004)001

4.8. References to books, conference proceedings and reports

References to books, proceedings and reports are similar to journal references, but have only two changes of font (see table ??).

Points to note are:

- Book titles are in italic and should be spelt out in full with initial capital letters for all except minor words. Words such as Proceedings, Symposium, International, Conference, Second, etc should be abbreviated to *Proc.*, *Symp.*, *Int.*, *Conf.*, *2nd*, respectively, but the rest of the title should be given in full, followed by the date of the conference and the town

Table 3. Font styles for references to books, conference proceedings and reports.

Element	Style
Authors	Roman type
Date	Roman type
Book title (optional)	Italic type
Editors	Roman type
Place (city, town etc) of publication	Roman type
Publisher	Roman type
Volume	Roman type
Page numbers	Roman type

or city where the conference was held. For Laboratory Reports the Laboratory should be spelt out wherever possible, e.g. *Argonne National Laboratory Report*.

- The volume number, for example vol 2, should be followed by the editors, if any, in a form such as ‘ed A J Smith and P R Jones’. Use *et al* if there are more than two editors. Next comes the town of publication and publisher, within brackets and separated by a colon, and finally the page numbers preceded by p if only one number is given or pp if both the initial and final numbers are given.

Examples taken from published papers:

- [1] Kurata M 1982 *Numerical Analysis for Semiconductor Devices* (Lexington, MA: Heath)
- [2] Selberherr S 1984 *Analysis and Simulation of Semiconductor Devices* (Berlin: Springer)
- [3] Sze S M 1969 *Physics of Semiconductor Devices* (New York: Wiley-Interscience)
- [4] Dorman L I 1975 *Variations of Galactic Cosmic Rays* (Moscow: Moscow State University Press) p 103
- [5] Caplar R and Kulisic P 1973 *Proc. Int. Conf. on Nuclear Physics (Munich)* vol 1 (Amsterdam: North-Holland/American Elsevier) p 517
- [6] Cheng G X 2001 *Raman and Brillouin Scattering-Principles and Applications* (Beijing: Scientific)
- [7] Szytula A and Leciejewicz J 1989 *Handbook on the Physics and Chemistry of Rare Earths* vol 12, ed K A Gschneidner Jr and L Erwin (Amsterdam: Elsevier) p 133
- [8] Kuhn T 1998 *Density matrix theory of coherent ultrafast dynamics Theory of Transport Properties of Semiconductor Nanostructures* (Electronic Materials vol 4) ed E Schöll (London: Chapman and Hall) chapter 6 pp 173–214

5. Tables and table captions

Tables should be numbered serially and referred to in the text by number (table 1, etc, **rather than** tab. 1). Each table should be a float and be positioned within the text at the most convenient place near to where it is first mentioned in the text. It should have an explanatory caption which should be as concise as possible.

5.1. The basic table format

The standard form for a table is:

```
\begin{table}
\caption{\label{label}Table caption.}
\begin{center}
\begin{tabular}{lllll}
\br
Head 1&Head 2&Head 3&Head 4\\
\mr
```

```

1.1&1.2&1.3&1.4\\
2.1&2.2&2.3&2.4\\
\br
\end{tabular}
\end{center}
\end{table}

```

The above code produces table ??.

Table 4. Table caption.

Head 1	Head 2	Head 3	Head 4
1.1	1.2	1.3	1.4
2.1	2.2	2.3	2.4

Points to note are:

- (1) The caption comes before the table.
- (2) The normal style is for tables to be centred in the same way as equations. This is accomplished by using `\begin{center} ... \end{center}`.
- (3) The default alignment of columns should be aligned left.
- (4) Tables should have only horizontal rules and no vertical ones. The rules at the top and bottom are thicker than internal rules and are set with `\br` (bold rule). The rule separating the headings from the entries is set with `\mr` (medium rule). These commands do not need a following double backslash.
- (5) Numbers in columns should be aligned as appropriate, usually on the decimal point; to help do this a control sequence `\lineup` has been defined which sets `\0` equal to a space the size of a digit, `\m` to be a space the width of a minus sign, and `\-` to be a left overlapping minus sign. `\-` is for use in text mode while the other two commands may be used in maths or text. (`\lineup` should only be used within a table environment after the caption so that `\-` has its normal meaning elsewhere.) See table ?? for an example of a table where `\lineup` has been used.

Table 5. A simple example produced using the standard table commands and `\lineup` to assist in aligning columns on the decimal point. The width of the table and rules is set automatically by the preamble.

<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>E</i>	<i>F</i>	<i>G</i>
23.5	60	0.53	-20.2	-0.22	1.7	14.5
39.7	-60	0.74	-51.9	-0.208	47.2	146
123.7	0	0.75	-57.2	—	—	—
3241.56	60	0.60	-48.1	-0.29	41	15

6. Figures and figure captions

Figures must be included in the source code of an article at the appropriate place in the text not grouped together at the end.

Each figure should have a brief caption describing it and, if necessary, interpreting the various lines and symbols on the figure. As much lettering as possible should be removed from the figure itself and included in the caption. If a figure has parts, these should be labelled (a), (b), (c), etc. Table ?? gives the definitions for describing symbols and lines often used within figure captions (more symbols are available when using the optional packages loading the AMS extension fonts).

Table 6. Control sequences to describe lines and symbols in figure captions.

Control sequence	Output	Control sequence	Output
<code>\dotted</code>	<code>\opencircle</code>	○
<code>\dashed</code>	- - - -	<code>\opentriangle</code>	△
<code>\broken</code>	- - -	<code>\opentriangledown</code>	▽
<code>\longbroken</code>	— — —	<code>\fullsquare</code>	■
<code>\chain</code>	— . —	<code>\opensquare</code>	□
<code>\dashddot</code>	— . . —	<code>\fullcircle</code>	●
<code>\full</code>	——	<code>\opendiamond</code>	◇

Authors should try and use the space allocated to them as economically as possible. At times it may be convenient to put two figures side by side or the caption at the side of a figure. To put figures side by side, within a figure environment, put each figure and its caption into a minipage with an appropriate width (e.g. 3in or 18pc if the figures are of equal size) and then separate the figures slightly by adding some horizontal space between the two minipages (e.g. `\hspace{.2in}` or `\hspace{1.5pc}`). To get the caption at the side of the figure add the small horizontal space after the `\includegraphics` command and then put the `\caption` within a minipage of the appropriate width aligned bottom, i.e. `\begin{minipage}[b]{3in}` etc (see code in this file used to generate figures 1–3).

Note that it may be necessary to adjust the size of the figures (using optional arguments to `\includegraphics`, for instance `[width=3in]`) to get you article to fit within your page allowance or to obtain good page breaks.

Figure 1. Figure caption for first of two sided figures.

Figure 2. Figure caption for second of two sided figures.

Figure 3. Figure caption for a narrow figure where the caption is put at the side of the figure.

Using the `graphicx` package figures can be included using code such as:

```
\begin{figure}
\begin{center}
\includegraphics{file.eps}
```

```
\end{center}  
\caption{\label{label}Figure caption}  
\end{figure}
```

References

- [1] IOP Publishing is to grateful Mark A Caprio, Center for Theoretical Physics, Yale University, for permission to include the `iopart-num` Bib_T_EXpackage (version 2.0, December 21, 2006) with this documentation. Updates and new releases of `iopart-num` can be found on www.ctan.org (CTAN).